Diurnal Patterns in the Persistence of "Thin-Layers" of Marine Snow, Zooplankton, and Turbulent Microstructure in Coastal Waters

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LONG-TERM GOALS

Accumulations of marine snow and phytoplankton in layers ranging from centimeters to meters have been observed in the coastal ocean and in fjords. These accumulations serve as foci for enhanced biological activity for microbes up to fish larvae. Our long-term goal is to develop a predictive understanding of how physical processes contribute to the formation of these layers as well as their eventual break up. Such information will allow determination of the contribution of thin-layers to the oceanic food chain, as well as determination of the impact of thin-layers on optical and acoustical properties of the water column.

OBJECTIVES

During 1999, we focussed on 3 main objectives: 1) determine the vertical patterns of distribution of marine snow in relation to density stratification, intrusions as identified by changes in temperature and salinity structure in the water column, and turbulence in the water column, 3) examine the significance of physical processes such as boundary mixing, subduction of water masses, shear, and turbulence in generating or dissipating thin layers of marine snow, and 3) relate patterns in the vertical distribution of marine snow, fluorescence, and turbulence to the biological, physical, acoustical, and optical properties of the water column as determined by our collaborators.

APPROACH

During 1999, we continued our analysis of data collected during the Thin-Layers Experiments in East Sound, Washington in May 1996 and June 1998. During these one and three week cruises, respectively, we obtained size distributions and abundances of aggregates of marine snow larger than 0.5 mm in diameter and profiles of temperature, salinity, and in vivo fluorescence using our still camera/instrument package (MacIntyre et al. 1995). Our temperature-gradient microstructure profiler was attached to the instrument package of Dr. Tim Cowles. This combined package allowed us to

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assess simultaneously the turbulent kinetic energy dissipation rate, water column hydrology, velocity on centimeter scales, and optical properties of the water column.

WORK COMPLETED

We have completed analyzing all 30 profiles of marine snow abundance obtained during the 1998 field study. We finished processing all the microstructure profiles from 1996 and the temperature-gradient microstructure casts for the days with most extensive layering of phytoplankton, with frontal structures, and with the greatest wind mixing in 1998. We deployed self-contained temperature loggers with time constants of 10 seconds and temperature resolution of 0.01 ^{o}C at depth intervals of 1 to 2m on moorings near the sill, near the CTD and TAPS arrays, and on the R.V. Henderson. We have computed isotherm displacements for this time series data and power spectra for selected times. We have prepared a map of bottom slope to be used in calculation of critical frequencies for wave breaking. We are preparing manuscripts with this data.

RESULTS

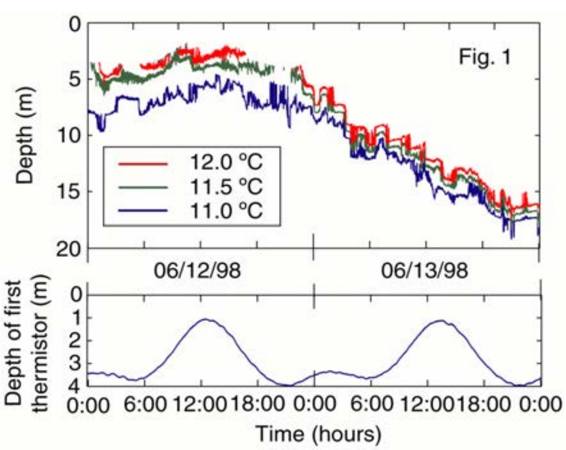
Processes likely to cause thin-layers include particles settling into water with comparable density, intrusions generated by boundary mixing (cf. Thorpe 1998; Bugucki et al. 1997), intrusions generated by mixing at fronts (cf. Browand et al. 1987), shear (Osborn 1998), and subduction of water masses at fronts. All these processes assume that there are initial differences in the spatial distribution of particles. For instance, layers of marine snow may form if there is high production of surface waters, flocculation, and subsequent settling into water whose density is comparable to that of the floc of marine snow. For thin-layers to be apparent after boundary mixing, concentrations of phytoplankton need to be higher inshore and subsequently advected offshore along isopleths. Sediments can be entrained by boundary mixing and thus form loci for bacterial activity in the water column. For layers to form after interaction of different water masses, the different water masses need to have different assemblages or concentrations of phytoplankton. As the layers of phytoplankton we have seen are within the euphotic zone, their growth will be enhanced if nutrient concentrations are different in the waters into which they are intruding. Interaction of Fraser River water and water from East Sound is one of the most likely reasons for formation of extensive, persistent layers in East Sound.

Thin–layers 1996 – Time series data of light attenuation (beam-C, 412 nm) showed a persistent layer in the upper 6 m of East Sound during the 24-hour study in 1996. The attenuation data indicated that particles were initially located between sigma-t of 20.6 to 21 kg m^{-3}. Twenty four hours later, the particles were located in waters with sigma-t ranging from 21.2 to 21.6 kg m^{-3}. While the maximum in light attenuation varied between 3 and 5 m depth and did track density fluctuations to a degree, the maximum tended to be between 3 and 4 m depth. These results suggest that some of the particles were not accumulating in waters of comparable density but may have been motile and seeking a particular irradiance level in the water column. Largest accumulations of marine snow were always below the maximum in beam–C and were either above or below water with sigma–t of 21 kg m^{-3}. That layers of marine snow were below the maximum in beam-C suggests that beam-C was indicative of phytoplankton or detrital particles smaller than 500 μm.

The layer of marine snow was likely being augmented continuously by settling particles. As no large accumulations of marine snow occurred below 8 m depth, either the sinking rate of the marine snow was reduced because of similarities of the density of the aggregates and the surrounding water, or

marine snow that sank further was disaggregated. Observations by divers indicated that marine snow deeper in the water column was older and was disaggregated. Rates of turbulent kinetic energy dissipation at depths with accumulations of marine snow and at depths deeper in the water column rarely exceeded 10^{-8} m^2s^{-3}. Consequently, it is unlikely that small scale shears due to turbulence caused disaggregation of layers of marine snow while we sampled. While infrequent, rates of turbulent kinetic energy at depths where phytoplankton abundances were higher did exceed 10^{-6} m^2s^{-3}. Consequently, small scale shears due to turbulence may have contributed to aggregation of marine snow. See http://www.crseo.ucsb.edu/biogeo for accompanying figures.

Thin-layers 1998- Time series temperature data from the array near the sill and near Donaghay's and Holiday's CTD and acoustic arrays showed jumps in the pycnocline depth accompanied by packets of high frequency waves (solitons) (Fig. 1). The formation of solitons near sills is well documented (Farmer and Armi 1999). However, the solitons that occurred near the sill are not in phase with those observed near the acoustic array. Those near the array are more likely caused by the constriction of the sound half way along its length. From noon on 12 June through the 13th, the pycnocline descended due to inflow of water from the Frazer River. Acceleration of the waters through the constriction may have led to the instability of the pycnocline. Alternatively, if internal waves are present in the sound, they are likely to become unstable at the constriction due to increased contact with sloping boundaries (Thorpe et al. 1996).



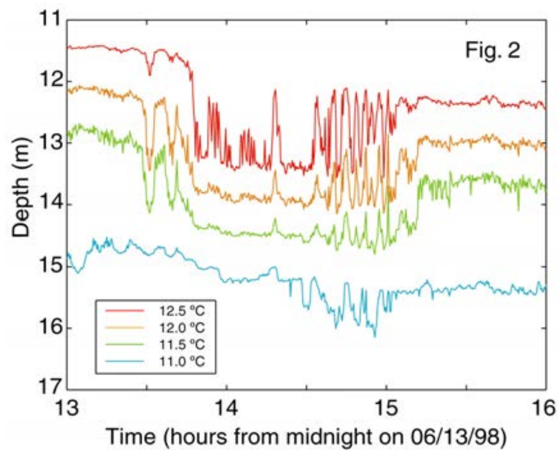
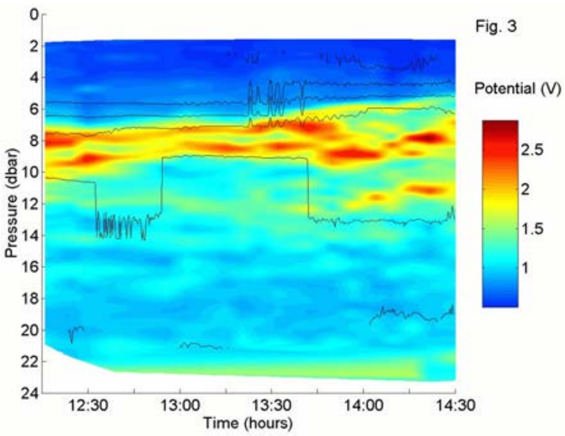


Fig. 1. Isotherm displacements within the pycnocline illustrating thermocline jumps and packets of high frequency waves, June 12 and 13, 1998. Tidal cycle is shown below. Low tide occurs around noon. Fig. 2. Expanded view of isotherm displacements. The pattern is similar to the thick and thin solitons described by Holloway et. al. (1999). These waves generate along slope flows likely to cause sediment resuspension (Thorpe et al. 1996).

Whether intrusions are likely due to boundary mixing depends on whether internal waves are near frequencies critical for wave breaking. Critical frequency f_c depends on water column stability given by the buoyancy frequency N and bottom slope α, $f_c = \alpha N$. Typical values of N in the water column range from 0.01 to 0.08 s^{-1}. Given that bottom slopes near the lateral boundaries of East Sound range from 0.2 to 0.8, critical frequencies range from 1 to 37 cph. Many of the high frequency wave packets are in the range critical for breaking. For example, those in Fig. 2 have a frequency of 14 cph.

Besides their role in generating intrusions, the solitons may also disperse layers or cause formation of new ones. Energy dissipation rates were up to 10^{-7} m^2s^{-3} in solitons. During the passage of solitons on 20 June 1998 at ca. 1330 hours, a layer of acoustic scatterers increased from 20 cm to 1 m in vertical extent. As the wave train initially passed, there were two layers of high fluorescence; by the end there was a third, less concentrated one in the pycnocline (Fig. 3). The new layer was generated at depths where energy dissipation rates had been highest. It persisted for another 5.5 hours. The layer that had initially been at 8 m depth disappeared after the solitons passed; it may have merged with the layer below. Current speeds did not change direction; consequently, it was not advected away.



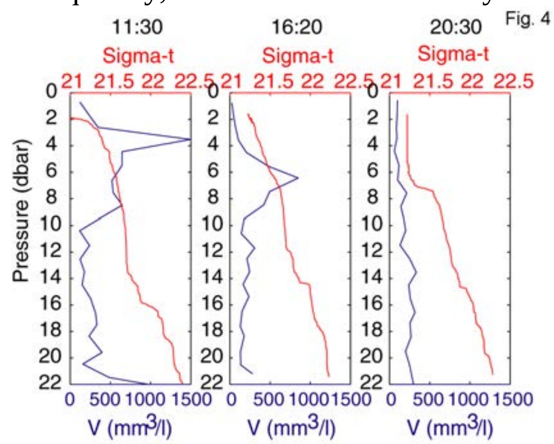
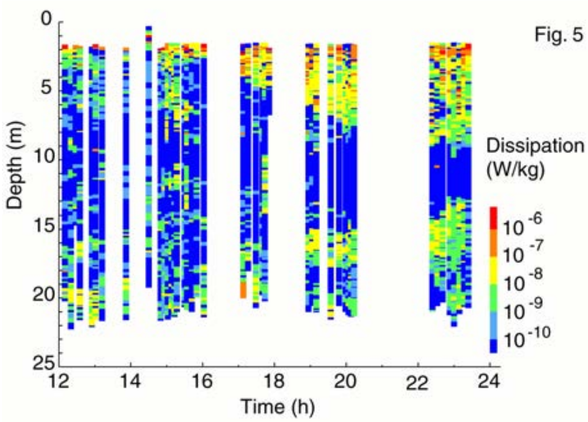


Fig. 3. Isotherm displacements (-) showing solitons interacting with a thin layer of phytoplankton between 6 and 8 m depth, 20 June 1998. A new thin layer was spawned in the pycnocline during this period. Colors represent fluorescence given in relative units. Fig. 4. Profiles of volume concentration of marine snow V and Sigma-t on 16 June 1998. Abundance maxima occur for sigma-t of ~ 21.5 in the first two profiles; shear dispersed the flocs by 2030h.

Pronounced layering of both marine snow and fluorescence occurred during the morning and afternoon of 16 June (Fig 4, 6). The wind came up in the afternoon increasing rates of turbulent kinetic energy dissipation (Fig. 5). The depth of the mixing layer, as indicated by $\varepsilon > 10^{-8}$ m^2 s^{-3} increased from 3 m at 1500 h to 8.5 m at 2230 h. Except when solitons were present, ε in the water above the fluorescence maximum tended to have values less than 10^{-9} m^2 s^{-3}; ε increased slightly at the top of the fluorescence maxima. When the wind driven mixing reached the pycnocline, fluorescence values had increased in the upper mixing layer. While the increase could be attributed to entrainment, we noted instead that a layer of warmer water had moved into the upper mixed layer and that currents had shifted from the southeast to the northwest. This water from elsewhere in the basin may have been the source of the increased fluorescence in the upper mixed layer. Fluorescence was not diminished in the pycnocline despite high shear, and at the end of our sampling period, we observed a layer of water with low fluorescence between the upper mixing layer and the pycnocline. These observations indicate that wind mixing is not necessarily a one-dimensional process. Instead, as water at different depths circulates in different directions, lateral intrusions induce or maintain distinct layers of fluorescence.

At 1130 and 1620 on 20 June, the maximum volume concentrations of marine snow occurred at the top of the fluorescence layer. Concentrations were high throughout the layer, and stayed high somewhat below the fluorescence maxima (Fig. 4). However, by 2030 h, there no longer was a maximum in volume concentration. Shear had been negligible in the pycnocline at 1930 hours, but by the time of

sampling had reached values of 0.05 s^{-1} between 6 and 8 m depth. Maximum energy dissipation rates had increased by an order of magnitude during this time period, and were up to 10^{-6} m^2s^{-3}. From 1620 to 2030 h, currents showed little change in direction in the pycnocline, and as fluorescence values in the pycnocline were similar at 2000 h and 2200 h, we hypothesize that shear had disrupted the large flocs of marine snow.



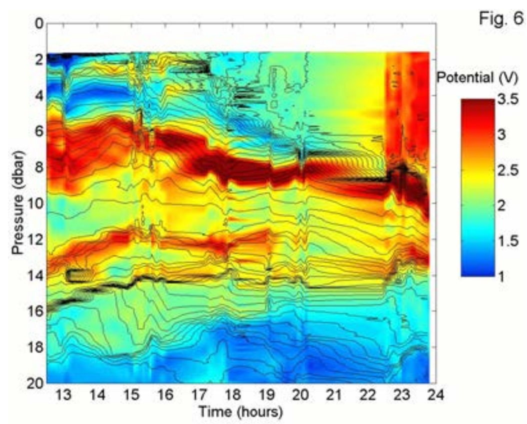


Fig. 5. Profiles of rates of dissipation of turbulent kinetic energy dissipation on 16 June 1998. Gaps in the record occurred due to sampling by other investigators.
Fig. 6. Density contours (-) and contours of fluorescence (colors) in relative units for the same time period. The microstructure profiler was on the same instrument package as the CTD and Flash Lamp Fluorometer.

IMPACT/APPLICATIONS

Our results highlight the importance of synthetic studies for understanding biological processes in the ocean. For instance, we now have a much better understanding of mixed layer dynamics due to our combined physical and biological measurements. While wind mixing is known to induce internal waves in the pycnocline, we saw it induce considerable shear in the pycnocline that disrupted large flocs of marine snow. We have documented that packets of high frequency waves are prevalent in environments with variations in topographic features; just as in East Sound, these waves will have frequencies critical for breaking. The intrusions that subsequently form will transport biogenic materials with consequences for ecosystem productivity.

TRANSITIONS

We are beginning an NSF sponsored study of boundary mixing and formation of intrusions with Steven Monismith and G. Schladow. Solitons are a persistent feature of the water bodies selected for the studies.

RELATED PROJECTS

We will continue our collaborative studies with other Thin-Layers Principal Investigators. We will investigate with Van Holiday the influence of solitons and turbulence on distributions of zooplankton as well as their impacts on marine snow. With Tim Cowles, we are assessing the importance of subduction to the formation of thin-layers and the importance of intrusions for generation of thin-layers of phytoplankton. With Diane Gifford, we are determining whether micrograzers are free-living or

associated with marine snow. With Mary Jane Perry, we will determine the importance of vertical mixing to primary productivity and nutrient supply. Jan Rhines is helping us determine the species of phytoplankton comprising marine snow. We are working with Percy Donaghay to further explore mechanisms leading to thin-layers. We are exploring the bioluminescence potential of the water column with James Case and graduate student, Christy Herren.

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PUBLICATIONS

Graham, W.M., S. MacIntyre, and A.L. Alldredge. In press. Diel patterns in the concentration of marine snow in surface waters. Deep-Sea Res.